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The Human Centrifuge

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Abstract Life on Earth has developed at unit gravity, 9.81 m/s^2, which was a major factor especially when vertebrates emerged from water onto land in the late Devonian, some 375 million years ago. But how would nature have evolved on a larger planet? We are able to address this question simply in experiments using centrifuges. Based on these studies we have gained valuable insights in the physiological process in plants and animals. They adapt to a new steady state suitable for the high-g environments applied. Information on mammalian adaptations to hyper-g is interesting or may be even vital for human space exploration programs. It has been shown in long duration animal hypergravity studies, ranging from snails, rats to primates, that various structures like muscles, bones, neuro-vestibular, or the cardio-vascular system are affected. However, humans have never been exposed to a hyper-g environment for long durations. Centrifuge studies involving humans are mostly in the order of hours. The current work on human centrifuges are all focused on short arm systems to apply short periods of artificial gravity in support of long duration space missions in ISS or to Mars. In this paper we will address the possible usefulness of a large human centrifuge on Earth. In such a centrifuge a group of humans can be exposed to hypergravity for, in principle, an unlimited period of time like living on a larger planet. The input from a survey under scientists working in the field of gravitational physiology, but also other disciplines, will be discussed.

Keywords Hypergravity · Artificial gravity · Microgravity · Weightlessness · Centrifuge · Gravity continuum · Mars · Moon · Human exploration · Human hypergravity habitat

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Introduction

In the past decades numerous studies have been performed on cellular, plant and animal development and adaptation for longer durations, even multi generations, under hypergravity conditions (see e.g. Beams and Kessel 1987; Hemmersbach et al. 1999; van Loon et al. 2005; Clément and Slenzka 2006). However, virtually no data are available on humans in long duration hypergravity.

When we divide gravity related research in human physiology, we can distinguish two main areas of research or application; the aero-medical and the space-related research. In the aero-medical field gravity fluctuations are relevant in flying modern, especially combat aircraft where steep maneuvers at high speeds are important or even crucial matters. It seems that the human being is one of the limiting factors in such systems (e.g. Pancratz et al. 1994; Convertino 1998; Scott et al. 2007). Both the cardiovascular and vestibulo-ocular systems are challenged to their limits. While going through the various combat maneuvers the pilots have to be trained to rely on on-board instrumentation with regard to orientation in stead of their own visual, proproseptive and vestibular sensors. They also have to be trained in special breathing techniques and wear anti-g suits to withstand the high g forces involved in support of their cardiovascular system. As the first field is mainly dominated by the military, the second field has emerged since mankind has decided to go into space. Related to spaceflight numerous experiments of some significant duration have been performed, first on board the Soviet Russian Salyut (Grigoriev et al. 1994) and later on the American Skylab crews (Johnston and Dietlein 1977) in the early 1970s. These cosmonauts/astronauts have been under near weightlessness conditions for several months and longer.

A Large Radius Human Centrifuge

Why would we need to explore the use of a ground based large radius human centrifuge?

A first and, in my view, very important reason to contemplate on a large centrifuge system is that the research emerging from this would be completely new, providing basic knowledge and understanding on how the human physiology is regulated with respect to sustained hypergravity. When we consider physical parameters acting upon the human body the factor weight is basically not any different from e.g. temperature or pressure, and in order to understand how the body deals with environmental variables we need to modulate them. Numerous studies have been performed exposing man to hypobaric and hyperbaric environments (see e.g. Miles 1957; Pedoto et al. 2003) or hypothermal or hyperthermal atmospheres (see e.g. Sawka et al. 2001; Solonin and Katsyuba 2003). So, what about gravity and humans? Most studies have been performed using relatively short-arm centrifuges and short exposure times. The average arm length of current centrifuges world wide is 7.6 m (Singh 2005). However, if one is interested in the long term effects of gravity on human physiology we need to expose humans to both hypo- and hyper-gravity conditions for periods of days or months. In his flying career the Russian cosmonaut Sergei Krikalev has been exposed to hypogravity conditions on board orbital space stations for more than 800 days. However, there has never been a person exposed to more than 1.0 g for such a period of time. The longest period to which humans have been exposed to hypergravity was few weeks during study performed in Dowley (California, USA) in the 1960s. In this facility 3–4 subjects lived in a camper size and like system attached to a large arm centrifuge. No publicly accessible publications have been released from this study. Recently NASA looked into the operation of a nearly 16 m diameter human centrifuge for studies in the order of weeks (NASA 2005).

Earth Bound Large Radius Centrifuge for Space Exploration

If the sole purpose of the application of a human centrifuge is to get humans on Mars, we could only focus on the recent developed short radius centrifuges (e.g. Cardus and McTaggart 1994; Iwasaki et al. 1998; Warren et al. 2006; Edmonds et al. 2007; Wuyts 2007). The main rationale for these relatively small centrifuges is that they would be applied on board a Mars mission. The radius has to be small in order to fit into a space system of some sort. The crew members are exposed to the artificial gravity in a supine position, with the subject's head near the center of rotation. This should be beneficial for the musculoskeletal and cardiovascular system while effects like Coriolis are still present.

However, if we elaborate a bit on the possible application of a large radius Earth based centrifuge in preparation of Moon/Mars missions, what could we use it for?

1. If we consider the paradigm of a gravity continuum, e.g. that physiological processes scale with the magnitude of applied acceleration (van Loon et al. 2005; Tou et al. 2002; Wade 2005) one may learn about the long term adaptation of the body to different g-loads. How fast does the human body adapt to the hyper-g load, but also how fast does the body respond when returning to Earth gravity after centrifugation? We might even combine such hypergravity studies with bed rest experiments before or after hyper-g exposure. Such studies provide valuable insights in adaptive processes also occurring in hypo-gravity adaptations.
2. We can apply a period of hypergravity to a Mars crew before their voyage to the planet. They might be pre-conditioned by building up enough "reserves" in terms of muscle and bone or any other system to overcome the microgravity and hypogravity periods of a mission to Mars.
3. It has been shown that humans can withstand a period in microgravity, while making use of various countermeasure devices, of much longer than a year as was shown in the flight by Valeriy Polyakov in 1994–1995 when he stayed on board the Mir station for 438 consecutive days. Based on this one might argue that we could go to Mars, a one way voyage of about 9–10 months without any new countermeasure protocols. If the adaptive effects for e.g. muscle, bone or the cardiovascular system have a higher threshold level than Mars gravity ($3.73\times g$) one could apply centrifugation on the Mars surface. This argument holds even more for

Moon missions where the weight is reduced to less than 17% from that on Earth, although the travel time is less relevant compared to a Mars mission. While on the planet the crew can be exposed to any suitable g-level, building up sufficient ‘reserves’ for their return trip to Earth. Such a centrifuge could have any suitable dimension not dictated by the size of the spacecraft transporting the crew to Mars.

4. If we consider a really large centrifuge, see later, there is an additional associated field of research namely psychology. Psychological issues are becoming more and more relevant as space mission durations increase. A round trip to Mars is in the order of 2–3 years (Horneck et al. 2003). Besides receiving large doses of radiation on a round trip to the red planet, social behavior and group dynamics within a limited crew of 6–8 persons is a major concern for such long missions (Palinkas 2001). This has not even taken into account the “Earth-out-of-view” impact (Manzey 2004). While conducting long duration hyper-g exposure studies on a crew size comparable to Moon or Mars missions we can, at the same time, study individual and group behavior and test various countermeasure procedures. In an on-ground centrifuge we have ample possibilities to make these investigations and as such a large centrifuge environment could be complementary to other space flight related analogues such as Antarctic station (Olson 2002). For on-ground centrifuge studies we could have a larger number of subjects in a series of experiments, in contrast to actual spaceflight studies, and we would have more than sufficient ‘crew time’ to perform measurements (Pawelczyk 2006). Also, the investigators involved could perform the measurements themselves, going into the centrifuge at the time of measurement.

What should the gravity level be? This is a difficult question. To answer this we could, as a first approach, rely on extrapolating data from long duration animal studies or short duration human experiments. From a very comprehensive study by Wunder et al. (1963) we could extrapolate a maximum value around 1.5 to 1.8×g. The limiting factor might be the body fluid balance (personal comment Dr. R. Burton). Bone and muscle systems are used to high loading although these peak loads are of short durations. Without a large radius centrifuge it is difficult to answer this question, however.

What can we expect from such a facility? Based on a survey among scientists active in the field of gravitational physiology spread over four continents some general conclusions might be drawn.

As mentioned before we can have insight in the adaptation of the human body to long duration hypergravity. Questions like: Does the paradigm of a gravity continuum also apply for humans? What is the adaptation time for the various organ systems, or their re-adaptation from hyper-g to 1 g or bed-rest? Psychological and social studies while running weeks or months hypergravity studies are advantageous in light of human exploration and long duration Mars and Moon missions. One might use such a system for sports or occupational training and explore possibilities for rehabilitation or diagnostics. While living and working in such a large centrifuge one could also perform studies in other areas besides human physiology like plant and animal physiology, combustion, or fluid and plasma physics. Also entertainment was mentioned as one of its possible applications. It was pointed out that, while living in such a system for longer periods of time the awareness of the outside world should be made comparable to normal every day life as much as possible.

What should be the size for such a centrifuge? Ideally we would only like to increase the acceleration acting upon the subjects without any side effects, as if you would live on a larger size planet. You should be able to live and work the same way as in unit gravity but now under 1.4 or 1.8 times Earth’s acceleration. Increasing

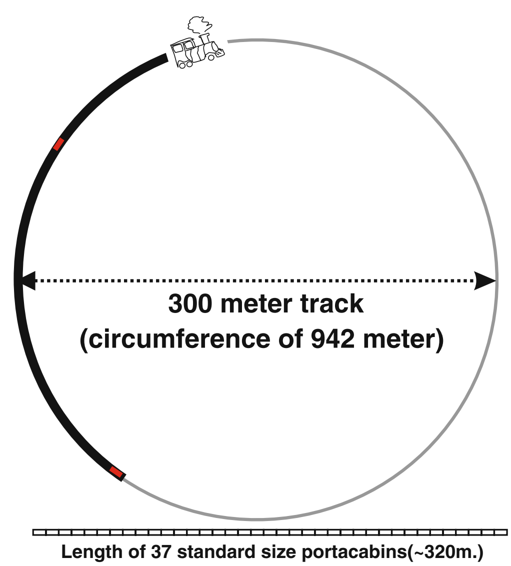

Fig. 1 First approach for a large diameter human centrifuge. A 300 m. diameter centrifuge should be something like a train track system. The total circumference would be 942 of which some 320 m. would be occupied by e.g. 37 standard size portacabins (see also Table 1)

Table 1 Possible division of the number of porta-cabin like building blocks for a train track like centrifuge occupying a crew of 6 persons

Purpose	Quantity
Personal living quarters	6
Kitchen	1
Cleaning	1
Communication	1
Common living room	2
Leisure	1
Physiology lab	3
Fluid science la	2
Physics science lab	2
Animal studies	2
Plant lab/green house	3
Biology lab	1
Supplies	4
Medical room	1
Exercise facility/gym	1
Engineering rooms	2
Workshop	1
Waste storage	2
Hub	1
Total	37

A number of blocks are needed when research in other fields as human physiology is conducted

the radius would be beneficial for artifacts such as Coriolis for the vestibular system or hydrostatic gradients (Hastreiter 1997) for the cardiovascular system. Effects of Coriolis are easily tolerated up to 2 rpm and adaptations could be acquired for up to 9 or 10 rpm (Reason and Graybiel 1970), however, some persons have a threshold as low as 0.2 rpm (Arlashchenko et al. 1963). The advantage of a large diameter would also enable the accommodation of a large number of subjects and associated infrastructure. Numerous studies have been published regarding centrifuge diameter and rotation speeds but nearly only for large in-flight structures including tether systems (Lansberg 1960; Ravera 1970; Newsom 1972; Davis et al. 1994; Lackner and DiZio 2000; Young 1999; Lansdorp et al. 2003; Clément and Pavy-Le Traon 2004; Hall 2006). Additional studies are required to determine a good or acceptable diameter for a ground based centrifuge. A combination of studies using both short arm and large radius centrifuges may be useful in uncoupling the dual adaptation effect of hypergravity and rotation (Lackner and DiZio 2000) once a large human centrifuge will become available.

The size of the system is still to be derived based on sub-threshold levels like for the vestibular system, cardiovascular system or gait issues. Since, for very large diameter systems, we cannot use the classical system of arms with a central motor, we need to think of a track-type system. Such a system was proposed in the early nineties by Burton et al. but only for a 30 m diameter track and mainly focused on military applications (Burton et al. 1991). Thirty two years before that a 152 m radius circular track system was proposed as part of a human launch simulator by NASA Marshall Space Flight Center (Gerathewohl 1961). In a first approach we might think of a centrifuge with diameter of some 300 m (see Fig. 1). This needs to be some kind of either conventional or magnetic levitating train track with a series of cabins to occupy the test subjects, their living and working quarters (laboratories), support rooms for leisure, storage, waste, energy, communication, workshop etc. (see Table 1). A gravity level of 1.5×g resulting from rotation on a 942 m track would result in a speed of 169 km/h with a rotation frequency of 3 rpm. This speed could be easily achieved by modern train systems but we need to maintain this speed for weeks or months without interruption.

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